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Augmentation of Studies into the Development and Evolution of Sedimentary Structures

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INTRODUCTION

Research work completed during this year included participation in the summer 1994 cruise of the *R/V Planet*, ongoing analysis of samples collected on cruises collected in 1993 and 1994, presentation of two talks at the AGU Ocean Sciences meeting, and submission of two papers to Geo-Marine Letters. This report presents current findings of our research on the sedimentology and benthic biology of Eckernfoerde Bay.

SEDIMENTOLOGY AND RADIOCHEMISTRY

Summary of work to date

Sedimentological studies were conducted in central Eckernfoerde Bay. Sediment is characterized by beds of clay-sized material, with slightly coarser laminations (~10% silt and sand). Excess ^{234}Th activity indicates that mixing is limited to the upper 5 mm of the seabed. Accumulation rates, measured by ^{210}Pb geochronology, range from 5 to over 10 mm yr^{-1}. The relatively high accumulation rates and absence of a significant mixed layer in the central bay allow fluctuations of sedimentological processes to be recorded in fine detail. Sediment-transport studies indicate that the laminated bedding is caused by alternating deposition of storm-suspended sediments from adjacent shallow-water areas and fair-weather supply of fine suspended material advected from the open Baltic.

X-radiography

X-radiographs of cores from the central basin of Eckernfoerde Bay show laminations in the upper 20-30 cm of the sea floor. The laminations are interbedded with thicker beds (several cm thick). Contacts between beds and laminations are diffuse. Laminations are generally more

absorptive of X-rays than the thicker beds (thus appearing dark in positive prints: Fig. 1), and may be laterally discontinuous and inclined from horizontal.

Microfabric

Two general types of microfabric were observed in cores from the central basin: pelletal fabrics (pellets > 10% of volume; percentages are approximate) and non-pelletal fabrics (pellets < 10% of volume). Of these, pelletal fabrics are by far the most common, and may be either matrix supported or pellet supported. Transitions from non-pelletal layers to overlying pelletal layers tend to be gradational, whereas contacts between non-pelletal and underlying pelletal layers are sharp (Fig. 2).

Pelletal fabrics tend to be anisotropic. Non-pelletal laminations sometimes display graded bedding (Fig. 2); other laminations may show no obvious grain-size variations between layers. In general, microstructural laminations correspond to laminations observed in X-radiographs, and pelletal fabrics in thin section are associated with thicker, homogenized beds seen in X-radiographs.

Grain-size distribution

Grain-size distributions tend to be polymodal, with the primary mode centered between 9.5 and 11.5 ϕ and a secondary mode, less than 10% by mass, centered between 3 and 6 ϕ (Fig. 3). Subtle coarsening in the median grain size of each mode is commonly associated with laminations observed in X-radiographs, and non-pelletal, graded bedding in microfabric (Fig. 3). The coarsening associated with these laminations is accompanied by a 2-4% increase in the mass percentage of particles in the 3-6 ϕ size range.

Radiochemistry

Sediment accumulation rates in the central basin determined by ^{210}Pb geochronology range from 3 to over 10 mm per year (Fig. 4). Excess ^{210}Pb is present in the seabed to depths of 30-40 cm (Fig 4). Excess ^{234}Th is restricted to the upper 5 mm of sediment, indicating that mixing is restricted to this thin veneer in the sea floor. No significant seasonal variability in sediment mixing depths was observed over winter, spring and summer cruises, although intensity may of mixing may change. Lateral variability of accumulation rates within the central basin was minimal.

Shallow penetration of sediment mixing results in the preservation of a detailed environmental record (cm-scale) in central-basin sediments. Long-term variations in ^{210}Pb profiles were observed in central-basin cores (Fig. 4), indicating historical shifts in either ^{210}Pb flux in coastal waters or changing sediment supply.

Sedimentary Event Layers

Once a sediment layer is deposited, it is then subject to modification by biological and physical mixing. In the absence of physical mixing, the degree of event-layer preservation in the historical sedimentary record is a function of the deposited-layer thickness, the sediment accumulation rate, and the depth and rate of biological mixing (Guinasso and Schink, 1975; Nittrouer and Sternberg, 1981; Wheatcroft, 1990, 1994). Events layers thicker than the mixed layer can be generated by unusual events (from large storms or floods), and can overwhelm the benthos, interrupting biological mixing (Wheatcroft, 1994). The physical record of such an event would be a bed or lamination with: a sharp lower boundary (resting on top of a bioturbated bed), a physically stratified lower layer, and a gradual increase upward in the intensity of bioturbation. This sequence has been widely recognized in coastal depositional environments (Frey and Howard, 1986; Leithold, 1989; Aigner and Reineck, 1982; Wheatcroft, 1994). The conceptual model is consistent with sedimentation in the central basin of Eckernfoerde Bay.

Depositional and Post-depositional Processes: Preserved Fabric

In order to assess the relationship between pulsed sediment deposition and rate of bioturbation, laminations were examined in thin section for evidence of progressive bioturbation with age. The laminations clearly preserved in thin sections (Fig. 2) have sharp lower contacts, and grade upwards into progressively more pelletized sediment. This trend indicates that degree of pelletization can be used as an estimate of bioturbation intensity following event-layer deposition, when the pellets under study are resistant to breakdown. The thicknesses of unburrowed sediment in event layers are on the order of 3-5 mm, comparable to progressively pelletized layers. Each preserved lamination must have been initially thicker than the sediment mixing depth in the central basin, otherwise the lower boundary would not have been preserved.

Excess ^{234}Th activities (Fig. 4) were used to estimate the biodiffusion coefficient D_b (~ 0.3 cm^2 yr^{-1}) in central basin sediments, using a solution to the steady-state advection/diffusion equation (Aller and Cochran, 1976),

$$D_b=\lambda(z/ln(C_0/C_z))^2$$

where λ is the ^{234}Th decay constant (10.5 yr^{-1}), z is depth in the seabed (cm), C_0 is excess activity at the surface (decays per minute per gram of sediment: dpm/g), and C_z is excess activity at depth z (dpm/g). The thin surface mixed layer resulted in only two subsamples containing excess ^{234}Th (Fig. 4). Because of the rapid mixing rates relative to accumulation rates, biological mixing is assumed to control the penetration of excess ^{234}Th into the seabed.

A method useful for assessing appropriate length and time scales of bioturbation is the decomposition of the biodiffusion coefficient into a mean step length and rest period (Wheatcroft

and others, 1990) using the form $D_b = \delta^2/2\Omega$, where δ is mean step length, and Ω is mean rest period (yr). Assuming a step length of 2 mm (a value appropriate to the benthic community, based on body length: G. Lopez, pers. commun.), the rest period is 24 days. To advect a 1 mm layer through the 5 mm mixed layer in less time than the rest period (and so preserve the layer) would require rapid deposition at rates equivalent to 7.5 cm yr^{-1}, one order of magnitude higher than the mean accumulation rates in the central basin (~7 mm yr^{-1}). Event layers exceeding the mixed-layer thickness satisfy these conditions.

Decadal-Scale Stratigraphic Record

Evidence of fluctuating accumulation rate is found on decadal scales, determined by ^{210}Pb geochronology (Fig. 4), as well as scales of single events, represented by non-pelletized laminations seen in thin sections (Fig. 2). Such fluctuations have been documented regionally (Balzer and others, 1986), and have been linked to winter-storm frequency and resultant resuspension and deposition (Khandriche et al, 1986). Shear velocities in the central basin have upper limits below critical erosion values (Friedrichs and Wright, in press), precluding significant physical sediment mixing. Biological mixing is seasonally intense, but is limited to depths (~5 mm) on the same order as annual accumulation rates (5-10 mm yr^{-1}). Thus, upper sediments of the central basin preserve a relatively high-resolution historical record (cm-scale) of sedimentary processes.

Conclusions

The sedimentary input to the central basin is controlled by pulsed supply of fine particles from both proximal and distal sources. Time-series benthic-boundary-layer observations (Friedrichs and Wright, in press) indicate physical sediment mixing to be insignificant. Biological mixing is intense, but presently limited to the upper 5 mm of seabed. Sediment pulses (storm layers) exceeding the mixed-layer thickness may be preserved as individual laminations. Slower deposition results in intensely reworked and pelletized sediment (pelletal fabric). Particle and chemical tracers reaching the seafloor may be vertically resolved to increments of ~5 mm, preserving a detailed stratigraphic record.

Fluctuations in the frequency of sediment pulses cause variations in ^{210}Pb accumulation rates (3-10 mm yr^{-1}). Similarly, sedimentary fabric (mm and cm scales) displays subtle gradients in grain size and bioturbation (including pelletization) that correlate to fluctuations in sediment supply rate.

BENTHIC BIOLOGY

Summary of work to date

The benthic macrofaunal community of Eckernfoerde Bay was characterized in terms of abundance and community structure. The community was dominated by small surface deposit-feeding animals. Faunal abundances in spring 1993 were 30,000-80,000 m^{-2}, and were 2,000-9,000 m^{-2} in summer 1994. Particle bioturbation was limited to the top 0.5-1.0 cm throughout Eckernfoerde Bay. Functional group classification, faunal abundances, organism size, and particle bioturbation are consistent with the hypothesis that the benthic community of Eckernfoerde Bay is controlled by a regular disturbance which maintains the community at a low level of complexity. All measured biological components are consistent with sedimentological and radiochemical studies which indicate a very thin layer (<1cm) of biological mixing.

Benthic Sampling

Benthic samples were taken during four ten-day cruises aboard the R.V. *Planet* and R.V. *Helmsand*, German naval research ships, during spring 1993 and summer 1994. Benthic sampling was focused around the acoustic tower deployment sites - Old Tower, New Tower - in the central basin (Fig. 5). Other samples were taken from the landward and seaward ends of the bay. These included both muddy sites - Eckernfoerde Navy Base, Stanic Tower, Hausgarten - and one sandy site, Mittelgrund. Three or more replicate box cores (20 x 30 x 50 cm) were collected per station. Three subcores were taken from each box core, were extruded, and sectioned into 0-2 and 2-10 cm sections. Animals were seived from sediment using a 500-µm sieve and preserved. Animals were identified to the lowest taxonomic group (usually species). Each taxonomic group was assigned to one of the following functional groups: surface deposit feeder, head-down deposit feeder, suspension feeder, or carnivore (see Table 1).

A bioturbation experiment was conducted to compare vertical particle mixing rates in different sediments and benthic communities. Three 15 cm diameter cores were collected from four stations along the axis of the bay - New Tower, Old Tower, Eckernfoerde Navy Base, Mittelgrund - in April 1993. Cores were maintained in a running seawater sytem at a shore lab. A 50 ml suspension of orange fluorescent particles (Radiant Pigment, 4-10 μm diameter, 1.4 sp. gravity) in seawater was added to the overlying water in each core, and allowed to settle onto the sediment surface for 24 hours. There was one control core and two experimental cores from each station. Nine to 12 subcores (10 ml syringe cores) were taken from each core. Subcores were vertically sectioned into 0-0.5, 0.5-1.0, 1.0-1.5, 1.5-2, 2-3, 3-4, and 4-5 cm intervals. Salinity and temperature were monitored during the course of the experiment. Experimental cores were incubated for approximately 2 weeks. Samples were analyzed for fluorescence of tracer particles

(modified from Carey 1989). All values were corrected for background fluorescence. Values from each depth interval were expressed as percent of the total fluorescence in that subcore.

Biological Observations

Macrofaunal abundance was high throughout the bay, dominated by small adults and juveniles of larger species. The dominant macrofauna consisted of 16 species (90% of total species) and 4 functional groups (Table 1). Benthic samples from the muddy stations - Old Tower, New Tower - in both 1993 and 1994 were dominated by small, numerous surface deposit feeders. The polychaete *Polydora ciliata* and the tellinid bivalve *Abra alba* accounted for 75-90% of all animals in many samples. Most of the *A. alba* were juveniles (<2.5 mm). Adult *Abra alba* were absent but their characteristic fecal pellets were abundant in the central basin; their presence indicates lateral transport from the sides of the basin. The surface deposit feeding cumacean, *Diastylus rathkei*, was numerically important in the June 1994 samples.

Abundances of surface deposit feeders in March-May, 1993 samples (27,000 - 73,000 m^{-2}) were significantly greater than the June-July, 1994 abundances (1,700 - 9,000 m^{-2}) (Fig. 5). Decreases in abundance were coupled with a shift in community composition at the muddy stations (Tower stations, Navy Base, Transect Station A, Hausgarten). The relative abundance of surface deposit feeders at the tower stations decreased from 80-90% in March-May 1993 to 60-85% in June 1994 (Fig. 6). Carnivores, especially *Harmathoe* sp. were proportionally more important in the June 1994 samples. The relative abundances of head-down deposit feeders remained unchanged between the two sampling years.

Mittelgrund is a sandy site near the mouth of Eckernfoerde Bay (see Fig. 5). This area supported a distinctly different fauna with significantly lower abundances than the muddy stations in the central basin. Mittelgrund had more head-down deposit feeders and a higher proportion of carnivores than the Tower sites (Fig. 6). Suspension feeders were also significantly more abundant in the sandier site.

The results of the particle mixing experiments showed that fluorescent particles were mixed approximately 0.5-1.0 cm into the sediment for all sites over a two week period (Fig. 7), regardless of functional group.

Our data indicates that the benthic fauna of Eckernfoerde Bay is dominated by small, surface deposit feeders, which do not mix particles deeply but probably mix the top cm of the sediment on short time scales (days). Differences in mean abundances between the two sampling years is thought to be seasonal (March-May in 1993 versus late June in 1994) and is consistent with previous work done in the Kiel Bight (e.g. Bosselman 1988, Meyer-Reil and others 1987, Rumohr and Arntz 1982).

The abundances and composition of benthic fauna in Kiel Bight is strongly linked to seasonal patterns of oxgen availability in the near-surface sediment (Kolmel 1979; 1977; Reimers; 1976). The benthic fauna of Kiel Bight typically experiences an exponential increase in abundance, dominated by small, tube-building polychaetes such as *Polydora ciliata*, from March to early June followed by a crash in June-July (Weigelt 1991; Bosselman 1988; Meyer-Reil and others 1987; Rumohr and Arntz 1982). In Eckernfoerde Bay, mean abundance of *P. ciliata* decreased an order of magnitude from the March-May 1993 sampling to the late June 1994 samples.

The primary controls on the benthic fauna of Eckernfoerde Bay during the study period were thought to be the rate of organic input to sediments, water column stratification, deep water mixing, and oxygen availability. During the spring bloom, carbon transport to the seafloor is between 10 and 15 g C m^{-2} and one-third of the yearly organic input can reach the seafloor of the Kiel Bight in 1-2 weeks (Meyer-Reil and others 1987). Portions of the Kiel Bight, particularly the southwest portion where Eckernfoerde Bay is located, are annually subjected to periods of hypoxia and anoxia in summer due to stratification of the water column and stagnant physical conditions (Weigelt 1991; 1990; Meyer-Reil and others 1987). We hypothesize that the low oxygen conditions that occur with water column stratification in Eckernfoerde Bay causes a regular disturbance which controls the complexity of benthic community structure.

All measured components of Eckernfoerde Bay - abundance, diversity, animal size, functional groups, particle mixing - point to a community dominated by pioneering species (sensu Rhoads and Boyer 1982), especially *Polydora ciliata* and *Capitella* sp., and a system controlled by a regular or recent disturbance which reduced the complexity of the community structure and sediment reworking by the benthic fauna. This is borne out by our bioturbation experiments (Fig. 7), our sedimentology and radiochemistry results, and with numerous German studies of the Kiel Bight (e.g. Weigelt 1991, Bosselman 1988, Meyer-Reil and others 1987, Rumohr and Arntz 1982).

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TABLES AND FIGURES

Table 1. Rank order of dominant macrofauna in Eckernfoerde Bay.

Fig. 1 X-radiograph positives, BS4-602 (Station N, Fig. 2) and BS4-611 (Station F, Fig. 2). Stations were separated by ~1 km. Note darker laminations (non-pelletized event layers). Thicker, light-shaded beds are intensely pelletized (see Fig. 2).

Fig. 2 Photomicrographs, BS4-602. Field of view is 5.5 mm wide. A) 2.5-2.8 cm depth, plane light: intensely pelletized horizon; fecal pellets produced by the surface-deposit-feeding bivalve *A. alba* B); 6.7-7.0 cm depth, crossed polars: upper portion of event layer showing transition from non-pelletized (lower) to pelletized fabric (upper); C) 7.0-7.3 cm depth, crossed polars: basal contact between non-pelletized event layer and underlying pelletized horizon.

Fig. 3 Grain size distributions. A) BS4-602, 1-2 cm; B) BS4-602, 3-4 cm. The 1-2 cm interval is characteristic of pelletized intervals, and the 3-4 cm interval, slightly coarser, is characteristic of non-pelletized event layers.

Fig. 4 Radiochemical profiles. A)Excess ^{210}Pb, BS1-85 (Station F, Fig. 2), note changes in accumulation rate through time; B) Total ^{234}Th, BS4-648, background levels are ~4 dpm/g and excess activities are restricted to the upper 5 mm.

Figure 5. Mean Abundances at Primary Study Sites, 1993: mean from three cruises in Spring, 1993, 1994: mean from one cruise in Summer, 1994. SDF = surface deposit feeders; HDF = head-down deposit feeders; C = carnivores; SF = suspension feeders; B = browsers. * = significantly different abundances than 1993 samples (α=0.05).

Figure 6. Percent Composition of Functional Groups by Station. SDF = surface deposit feeders; HDF = head-down deposit feeders; C = carnivores; SF = suspension feeders; B = browsers.

Figure 7. Vertical profiles of percent fluorescence (means and standard deviations) at primary study sites. Values are corrected for background fluorescence. Stations: O = New Tower, F = Old Tower, H = Eckernfoerde Navy Base, G = Mittelgrund.

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